2013

Ravine 8 Ecosystem Restoration

Appendix A – Hydraulics & Hydrology

Alternative Formulation Briefing Document

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INTRODUCTION

The issues present in Ravine 8 that were the focus of this project were addressing the storm sewer outfalls discharging at the heads of the main channel and southern tributary of the ravine, reducing the channel velocities within the ravine that currently are inducing downcutting and reestablishing hydraulic connectivity with Lake Michigan. Of the measures considered, the only feasible options involve bypassing the storm sewer discharge through an in-ravine pipe and addressing the velocities of the reduced flows that remain within the channel or providing sufficient channel stabilization measures to mitigate for velocities within the channel.

SITE DESCRIPTION

Ravine 8 is approximately 800 feet long and has a tributary area of approximately 28 acres consisting entirely of single family homes. The City of Highland Park has recently completed the installation of a sanitary sewer along the bottom of the ravine, terminating at the Interceptor running perpendicular to the ravine along the beach. Upon completion of the installation, the sanitary sewer was backfilled with clay and the new ravine floor modestly regraded. The storm sewer at the head of the ravine was modified so that the outfall discharges to the new ravine floor, as shown in **Figure 1**.

Figure 1- Storm Sewer Outfall at Head of Main Channel

The second storm sewer outfall discharging to Ravine 8 is located at the head of the southernmost tributary, shown in **Figure 2**. Although the actual location of the outfall was not determined during site visits, the final run of pipe was found below the broken concrete cap visible to the left of the retaining wall in **Figure 2**. Due to the failure of the concrete and apparent erosion and sloughing below the last visible length of pipe, it is assumed that the pipe has failed and is washing out the substrate below the concrete.

Figure 2 - View of Southern Tributary from Confluence

Since the completion of construction, the remainder of the ravine has experienced varying degrees of downcutting. The most significant of this occurs at the mouth of the ravine, as shown in **Figure 3**.

Figure 3 - Downcutting at Mouth of Ravine 8

At the time of the site visit in early November 2012, the depth of the channel exceeded one foot in some locations. In anticipation of erosion issues, during the construction of the sanitary sewer along the ravine the City of Highland Park constructed a check dam using rubble found within the ravine, shown in **Figure 4**. The majority of the flow passes over the check dam, but a small amount has begun to flank the structure. The mouth of the ravine is positioned on the updrift side of a groin sufficiently far inland that it does not appear as through wave action will be of significant concern.

Figure 4 - Improvised Check Dam at Mouth of Ravine 8

HYDROLOGIC & HYDRODYNAMIC DATA COLLECTION

Data collection and the initial estimation of parameters used to hydrologically model the ravine included in this study are discussed in this section. Data collection activities included subbasin delineation, current land-use, and soils information compilation.

Subwatershed Delineation

Subwatersheds were generated using HEC-GeoHMS and a 10-foot digital elevation model (DEM) that was provided by Lake County. The DEM was developed using deliverables from a LiDAR survey taken in April 2002 in support of the County's efforts to develop 2-foot contours. The resolution of the DEM was not sufficient to capture the curbs and gutters of the street, so the subwatersheds representing the streets were manually adjusted to reflect the sewers. They were then further divided to facilitate the development of the SWMM model. The original delineation is shown in **Figure 5** while the final delineation is shown in **Figure 6**. Acreage of each subwatershed is shown in **Table 1**.

Soil Information Compilation

Soil maps created as part of the National Cooperative Soil Survey (NCSS), which is led by the USDA-NRCS, were used for classifying the hydrologic characteristics of the soils in the watershed. The USDA-NRCS soil categorization scheme contains the soils coverage Map Unit Symbol (MUSYM) attribute. The MUSYM is the same soil survey designation as the Soil Conservation Service (SCS) designation and corresponds to the hydrologic soil group for soil types A through D, but has four additional categories. The project area consists of hydrologic soil group type C.

Figure 5- Original HEC-GeoHMS Subwatersheds

Figure 6- Adjusted Ravine 8 Subwatersheds

Table 1 - Subwatershed Drainage Areas

Subwatershed Name	Area (acres)
Ravine - Main #1	0.45
Ravine - Main #2	4.66
Ravine - Main #3	1.6
Ravine - Offshoot #1	2.99
Ravine - Offshoot #2	0.71
Ravine - Offshoot #3	0.65
Ravine - Tributary #1	1.02
Ravine Tributary #2	1.89
Street - Crescent	2.75
Street - W. Prospect #2	2.79

Subwatershed Name	Area (acres)
Street - E. Laurel #1	0.15
Street - E. Laurel #2	1.09
Street - E. Prospect #1	0.46
Street - E. Prospect #2	0.37
Street - Lake #1	0.8
Street - Lake #2	0.39
Street - Lake #3	2.64
Street - Lake #4	1.12
Street - Lake #5	0.79
Street - W. Laurel	0.93
Street - W. Prospect #1	1.71

HYDROLOGIC AND HYDRAULIC MODELING USING SWMM 5.0

The hydrology of the ravine's subbasins and the flow routing through the ravines were modeled using version 5.0 of EPA's SWMM model. EPA-SWMM represents the watershed as an interconnected system of subbasins that simulate the precipitation runoff process and hydraulic components that connect the subbasins, and models a storm sewer network through a series of conduits and junctions. Each component is represented by a set of parameters that specify the physical processes. Inputs to the SWMM model include subbasin area and its interconnectivity, hydrologic parameters, and physical characteristics of the storm sewer infrastructure. The result of the model is the hydrographs at the outlets of the storm sewers where they discharge to the ravines.

Subcatchment Parameters

Subcatchment parameters included such things as overall area, characteristic width, percent slope, percent impervious, Manning's n, depth of depression storage, percentage of impervious area without depression storage, and SCS curve number. Subcatchment area and percent impervious were based on measurements taken from aerial photography in ArcGIS. The characteristic width is defined as the area divided by the longest flow path, which was estimated using topography and aerial photographs. The average percent slope was estimated using the DEM and longest flow path – elevations were taken at distances corresponding to 85% and 15% of the longest lengths and the slope defined using the distance between these points. The values for Manning's n were left at their default values of 0.01 and 0.1 for impervious and pervious areas, respectively. Similarly, the values for depth of depression were left at their default values of 0.05. These values can be used to calibrate the models should data become available later on. The SCS curve number applied to the pervious area only and was defined as 74.

Storm Sewer Data

Storm sewer data was provided by the local municipality and consisted of information relating to pipe size and invert elevations, structure rim elevations and outfall invert elevations. Not all of the structures included in the model were adequately documented in the provided data. An additional field survey was conducted to supplement the dataset. This information was used as input into the model.

Model Calibration

Calibration of the SWMM models was not possible due to the absence of storm sewer monitoring data. While this will contribute to additional inaccuracies in the outfall hydrographs, there is still a sufficient amount of confidence to permit the model to be used. The storm sewer geometry was generated from data collected by the local sponsors and/or through field surveys. Any differences between this data and what actually exists is assumed to be limited by the accuracy with which it can be measured (i.e. it is assumed that data provided by the local sponsors is correct unless obviously questionable). As the majority of the data was provided to the nearest hundredth of a foot, the impact of these inaccuracies upon the outfall hydrographs should be minimal. The greatest source of error in the model will manifest in the estimation of the characteristic basin width. While this value is commonly used as a calibration parameter for the timing of the hydrographs (which can become an issue depending upon the complexity of the storm sewer network), the absence of calibration data makes an adjustments from the baseline value impractical. Although the final output may not be perfectly representative, it provides a reasonable approximation for the storm sewer's response to design storm events. For the purposes of the feasibility level of design, any inaccuracies in the modeling results can be accounted for through a more liberal application of a safety coefficient for proposed measures.

Precipitation Data

Without data to calibrate the models, observed precipitation data was not required. Instead, the models used synthetic events to drive the output. Frequency distributions were developed using Rainfall Depth Duration Frequency Table from the Lake County Stormwater Management Commission's Watershed Development Ordinance. The Huff quartile distributions applicable to areas of less than 10 square miles were applied to the total rainfall depths. The synthetic rainfall depths and distributions are shown in Appendix C.

DEVELOPMENT OF THE HEC-RAS HYDRAULIC MODEL

The hydraulics of Ravine 8 were modeled using version 4.1 of USACE's HEC-RAS software. The HEC-RAS model for the ravines consists of several component data sources including channel geometry, roughness parameters, and flow/stage boundary conditions.

Cross-Section Geometry

The geometry data used in the HEC-RAS model was assembled primarily using the 10-foot DEM provided by Lake County. Cross-section cutlines were defined approximately every 100 feet. In advance of the project, the City of Highland Park completed a sanitary sewer construction within the ravine. As-built drawings provided by the City of Highland Park included contours indicating pre-construction topography of the ravine and a profile showing the centerline elevation after they had finished grading. For the purposes of the feasibility study, it is assumed that the final grading of the ravine will be approximately the same as the current condition. The cross-sections developed from the DEM were modified to best represent the current condition by modifying the lower elevation points to match the provided contours and raising the channel bed to coincide with the provided profile.

Friction Roughness Factors

Manning's n values were determined using notes taken from field observations and photographs taken of the site. The median Manning's n value for a given surface was selected as the initial value. The reference tables used to determine roughness values are included in Appendix A.

HEC-RAS Boundary Conditions

The HEC-RAS model was run as a mixed flow regime model, allowing for both upstream and downstream control. Discharges at the heads of the ravines are supplied by sewer outfalls and the mouths are assumed to be free flowing without backwater effects, so critical depth was used as both the upstream and downstream boundary condition.

HEC-RAS Discharge Data

For the recommended plan, the subwatersheds serviced by a storm sewer would be directly connected to the in-ravine pipe, thereby bypassing floor of the ravine. The remaining flows that must be accounted for in the HEC-RAS model are those that are attributed to overland flow from precipitation that falls onto a subwatershed that drains directly to the ravine. Peak flow rates from the SWMM model for these five subwatersheds, as shown outlined in **Figure 7**, were identified for the 6-, 12-, 24-, 48-, and 72-hour 100-year rainfall events. Although these subwatersheds are defined in the SWMM model to discharge to the downstream end of the basin, to develop a conservative design the flow is applied to the entire channel

(i.e. the immediate head of the ravine is assumed to have the same flow rate as at the most downstream cross-section of its particular basin). The peak flows for subwatersheds upstream of a given location are included in the total flow (i.e. the mouth of the ravine is the sum of all the upstream subwatersheds).

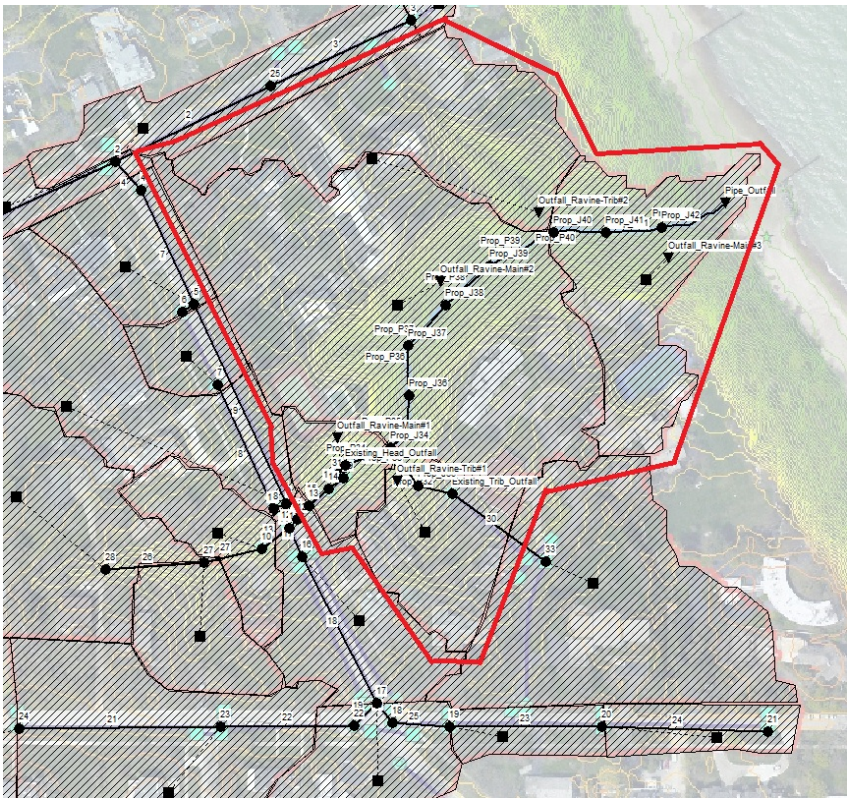


Figure 7 - Subwatersheds Contributing to Overland Flow

Model Calibration

Calibration of the HEC-RAS model was not possible due to the absence of observed gage data, but the results of the modeling are nevertheless useful for the purposes of this study. The geometry data was developed using a combination of LiDAR data and observations and measurements made in the field. Although the results of the HEC-RAS models will be influenced by the errors introduced through the flow data input generated by the EPA-SWMM model and the error in the approximation of the channel geometry, these can be negated through the liberal application of a safety coefficient in the design of any proposed measures.

PROPOSED REMEDIATION METHODS

This section details the toolbox of measures employed in this study and any assumptions that may have been made. Individual design calculations for the measures included in the recommended plan can be found in Appendix D.

Riffle Design

Establishing a stable grade in an eroding channel is an important step in a restoration project and grade control structures have long been used for this task. Increasing channel stability is typically accomplished by providing a fixed point in the bed and decreasing channel slope through sedimentation upstream of the structure. Many traditional grade control structures, however, have undesirable consequences when included in ecosystem restoration projects. While providing the same stabilization benefits of traditional grade control structures, riffles allow for the opportunity to create habitat and increase reoxygentation.

The consideration for the inclusion of riffles within a reach of a ravine was based on the results from the HEC-RAS modeling. For the purposes of this feasibility study, it was assumed that flow velocities exceeding 3.5 feet per second would result in the suspension of both fine and coarse sediments. Locations where this threshold velocity was exceeded were selected for the placement of riffles. When these reaches extended across multiple cross-sections, they were further subdivided into groups of similar slope.

The design methodology adopted for this project is detailed in EMSR 4-XX. In this method, the riffle spacing is based on a limiting slope, S_L. In the absence of data describing the grain size distribution of the sediment, it was necessary to make an assumption of the limiting slope. The results of the HEC-RAS model were again employed. The cross-sections adjacent to the reach in question typically had a similar profile and the same flow rate. Once it had been confirmed that the resultant velocity for these cross-sections was below the threshold value, the channel slope was measured and used as the limiting slope.

Having identified a limiting slope, the relationship used to compute the amount of drop removed between the riffles is as follows:

$$H = (S_o - S_L)x$$

In this equation, H is the amount of drop removed in the reach, S_O is the original bed slope, S_L is the limiting bed slope, and x is the length of the reach. The maximum total drop across the length of a riffle was typically based on the depth of channel incision within the reach. The total drop removed in the reach, H, was divided by the drop across each structure to determine the required number of structures.

The stones for the weir were sized using conventional riprap design guidance as provided in EM 1110-2-1601. This guidance provides a modification to the Maynord equation as follows:

$$d_{30} = C\left[\left(\frac{\Gamma_W}{\Gamma_S - \Gamma_W}\right)^{0.5} \times \frac{V}{\sqrt{K_1 g d}}\right]^{2.5}$$

$$C = SF \times C_S \times C_V \times C_T \times d$$

In this equation d_m is the stone size m percent finer by weight, SF is the factor of safety, C_S is the stability coefficient, C_V is the velocity distribution coefficient, C_T is the thickness coefficient, d is the depth of flow, Γ_X is the specific weight of stone or water, V is the local velocity, and K_1 is the side slope correction. Guidance in EM 1110-2-1601 recommends a stability coefficient of 0.375 for rounded rock, a velocity coefficient of 1.0 for straight channels, and a local velocity to be equal to 160% of the channel velocity. Since the stones are placed in the bed, the side slope correction can be assumed to be equal to

unity. The thickness coefficient can be assumed to be equal to unity provided that the design criteria outlined in EM 1110-2-1601 is followed.

The configuration of the riffles consists of a series of stones constructed with an upstream slope of 1V:4H and a downstream slope of 1V:10H. The design documentation recommends an interior angle of approximately 120 degrees, but there can be significant variability to this estimate. A narrow channel, which many of the reaches could be characterized as being, may prohibit any shape other than a line of stones perpendicular to the channel. The angle of the stones will deflect flows from the banks and thus provide a measure of local bank protection. To reduce the possibility of flanking, the entire structure should be keyed into the banks.

It can be expected that water would initially flow freely through the voids in the stones until they become filled with suspended sediment, provided that there is an adequate supply. To accelerate this process and thereby reduce the impacts further downstream due to interruption of the natural sediment load usually conveyed the area behind each riffle will be prefilled with alluvium consistent with that typically found on site.

In-Ravine Pipe Design

Through this remediation method, storm sewer flows bypass the ravine and are routed directly to the beach. While this method preserves the ravine slopes and adjacent structures at the top, the floor of the ravine is sacrificed, as are any improvements to water quality that could have been gained through attenuation and filtration in the ravine.

The in-ravine pipe systems were designed using a variation of the existing condition SWMM model. The outfall for each storm sewer would remain in place, but would be directly connected with the proposed in-ravine pipe. The in-ravine pipe would buried along the centerline of the ravine under approximately 2 feet of cover. Additional manholes were placed at junctions as needed. The critical duration for the 100-year rainfall event was used as the design condition for the sizing of the pipe diameters. Assuming a minimum pipe size of 30” for a single pipe and 18” for two pipes, the in-ravine pipe’s performance was reviewed during 100-year rainfall events of 6-, 12-, 24-, 48-, and 72-hour durations.

Stone Apron Design

Whenever a pipe or other conduit discharged a flow to a natural channel or surface, the concentrated flow necessitated the use of some sort of stone armoring to prevent the development of scour at the base of the structure. The stone apron design outlined in FHWA’s HEC-14 manual was selected for this application. While the design does not dissipate significant energy except through increased roughness for a short distance, it does aid in the transition to the natural channel by distributing the flow across the entire channel. These measures were typically included at the base of outfalls discharging to the beach.

The median required stone size, D_{50} is calculated by:

$$D_{50} = 0.2D\left(\frac{Q}{D^{2.5}\sqrt{g}}\right)^{4/3}\left(\frac{D}{TW}\right)$$

where Q is the design discharge, D is the culvert diameter, TW is the tailwater depth, and g is the acceleration due to gravity. Since the tailwater depth was generally unknown, 0.4D was used instead per guidance found in HEC-14.

Once a stone size has been estimated, Table 10.1 of HEC-14, shown below (**Table 2**), is entered to determine the recommended apron dimensions.

Table 2 - Riprap Classes and Apron Dimensions (Table 10.1 from HEC-14)

Class	D_{50} (mm)	D_{50} (in)	Apron Length	Apron Depth
1	125	5	4D	$3.5D_{50}$
2	150	6	4D	$3.3D_{50}$
3	250	10	5D	$2.4D_{50}$
4	350	14	6D	$2.2D_{50}$
5	500	20	7D	$2.0D_{50}$
6	550	22	8D	$2.0D_{50}$

MEASURE IDENTIFICATION

HA – Open Channel Conveyance

This measure seeks to address the existing storm water discharge without providing attenuation or redirection of the flow. Additional armoring of the ravine channel will be required to resist the velocities at several locations along the ravine. Connectivity to the lake will be restored by the removal of the check-dam at the mouth of the ravine. The slope will be regraded to a distance of approximately 200' upstream of the mouth.

The energy from the storm sewer outfall would first be dissipated in a plunge pool located directly below the existing outfall structure. The pool would be ten feet long, nine feet wide, six inches deep, and consist of D_{50} = 0.5 feet with a thickness varying between 1.5 and 1 foot. A five foot long apron would provide a transition from the plunge pool to the ravine channel.

A total of fifteen riffles would be constructed in the finished grade (in effect the cells upstream would be prefilled) to mitigate for the high velocities. Between cross-sections 727 and 512 fourteen 6" riffles using D_{30} = 0.3 foot stone would be constructed every 15.3 feet. Between cross-section 224 and approximately 200 feet upstream of the ravine's mouth an additional 6" riffle using D_{30} = 0.3 foot stone would be constructed. The final slope to the beach would require twelve 18" riffles using D_{30} = 0.3 foot stone spaced every 16.7 feet.

HB – In-Ravine Pipe Conveyance

The measures involving rerouting the flow through in-ravine pipes considered two options – one using a single 30" diameter pipe and the other a pair of 18" diameter pipes. The measure selected for plan formulation was the single 30" diameter pipe. Connectivity to the lake will be restored by the removal of the check-dam at the mouth of the ravine. The slope will be regraded to a distance of approximately 200' upstream of the mouth.

In the proposed measures for Ravine 8, the existing storm sewer would be integrated into a manhole, capturing and directing the flow to the proposed in-ravine pipe. The 30" diameter pipe would trenched and backfilled under the centerline of the ravine and be placed on a 6-inch bed of coarse aggregate. The sewer outfall at the head of the southern tributary would be replaced with a 15" diameter pipe that would convey the discharge directly to the proposed in-ravine pipe. Access manholes would be placed at the maximum interval allowable by the local municipality and as necessary to accommodate bends in the ravine. Approximately 200 feet from the mouth of the ravine the pipe will jog slightly off-center and run

under the toe of the ravine slope. This is necessary to accommodate the transition from the elevated profile to the elevation of the beach while maintain connectivity to the upstream portions of the ravine for fish passage.

Although the majority of Ravine 8's current flow will be rerouted through the proposed in-ravine pipe, a modest amount will remain due to groundwater discharge and rainfall falling directly on the 9.6 acres of ravine and bluffs immediately adjacent to the ravine. While the flow rate would be modest, the removal of the check dam could generate sufficiently steep slopes where high velocities could be generated, creating the potential for downcutting and the gradual unraveling of the ravine. To reduce these slopes, riffles would be constructed in the finished grade (in effect the cells upstream would be prefilled). From the start of the final slope to the mouth of the ravine twelve 18" riffles using D_{30} = 0.3 foot stone would be constructed every 16.7 feet.

A stone apron would be necessary at the in-ravine pipe's outfall. It would require stones D_{50} = 1.1 feet in diameter laid 3.6 feet thick. The apron would be 7.5 feet wide at the pipe's outfall, 14.2 feet wide at the downstream end, and 10 feet long.

HC – Underground Detention Storage

This measure would attenuate the flows from the storm sewer outfall using underground detention storage. Connectivity to the lake will be restored by the removal of the check-dam at the mouth of the ravine. The slope will be regraded to a distance of approximately 200' upstream of the mouth. The peak discharge would be sufficiently low to minimize the downstream channel velocities. Riffles would be constructed in the finished grade (in effect the cells upstream would be prefilled). From the start of the final slope to the mouth of the ravine twelve 18" riffles using D_{30} = 0.3 foot stone would be constructed every 16.7 feet.

PROPOSED ANALYSES FOR DESIGN & IMPLEMENTATION PHASE

As noted in Sections Development of the HEC-RAS Hydraulic Model and Proposed Remediation Methods, without stage and flow data to calibrate the models, an element of uncertainty to the models will remain. While the failure of the design due to this lack of information can be avoided through an increased safety factor, this creates the potential for over-design. By collecting gage data in the ravine and sewers the confidence in the appropriateness of the design can be increased.

The proposed riffle designs should be incorporated into the HEC-RAS geometry files to refine the specified depths and velocities, allowing for the modification of the selected stone size as necessary. The stone sizing for the riffles should be computed for a variety of durations. This will not only allow for a refinement of the design parameters, but also the potential for a reduction in size or number of riffles and a resultant increase in the length between structures.

The potential influence of wave runup on the stability of the apron and final riffle should be investigated, particularly during conditions of high lake levels and severe storm surge. If the risk of dislodgment is serious, increases to the stone sizes should be considered.

The proposed riffles along the final slope of the ravine result in a nearly continuous armored surface. The use of a step-pool system should be considered instead. Rather than mitigating the potential for scour by lengthening the distance the elevation drop occurs, the step pool system would allow for a rapid drop and a pre-engineered pool. Additional modeling work would be necessary to determine the critical 2-year and 25-year rainfall events.

REFERENCES

Cowan, W.L. *Estimating Hydraulic Roughness Coefficients.* Agricultural Engineering, 37(7), pp. 473-475, 1956.

Biedenharn, D. S. and Hubbard, L. C. *Design Considerations for Siting Grade Control Structures.* CHETN-VII-3. U.S. Army Corps of Engineers, Washington, D.C. December 2001.

Federal Highway Administration. *Hydraulic Design of Energy Dissipators for Culverts and Channels*. HEC-14, Third Edition. 2000.

Fripp, J., Fischenich, C., and Biedenharn, D. *Low Head Stone Weirs*. Technical Note EMSR 4-XX. United States Department of Agriculture. Date Unknown

Greengard, Inc. *Stormwater Management Report*. File 52180. October 2008.

Huff, F.A. and Angel, J.R. *Frequency Distributions of Heavy Rainstorms in Illinois (Circular 172).* Illinois State Water Survey. 1989.

Huff, F.A. and Angel, J.R. *Rainfall Distributions and Hydroclimatic Characteristics of Heavy Rainstorms in Illinois (Bulletin 70)*. Illinois State Water Survey. 1989.

Huff, F.A. *Time Distributions of Heavy Rainstorms in Illinois (Circular 173).* Illinois State Water Survey, 1990.

Hydrologic Engineering Center. *HEC-HMS Hydrologic Modeling System User's Manual*. CPD-74A Version 2.1. U.S. Army Corps of Engineers. January 2001. http://www.hec.usace.army.mil/software/hec-hms/documentation/CPD-74A_2001Jan.pdf

Hydraulic Engineering Center. *HEC-RAS River Analysis System User's Manual*. CPD-68 Version 4.0. U.S. Army Corps of Engineers. March 2008.

Natural Resources Conservation Service (Formerly Soil Conservation Service). *Urban Hydrology for Small Watersheds: Technical Release 55*. Second Edition, June 1986.

Sturm, T.W. *Open Channel Hydraulics*. New York: McGraw-Hill, 2001.

U.S. Army Corps of Engineers. *Hydraulic Design of Flood Control Channels*. EM 1110-2-1601. June 1994.

U.S. Department of Agriculture – Soil Conservation Service. *Technical Release 55 – Urban Hydrology for Small Watersheds*. 210-VI-TR-55. U.S. Department of Agriculture. June 1986.

APPENDIX A – ESTIMATING HYDRAULIC ROUGHNESS COEFFICIENTS

Roughness Coefficients for Sheet Flow Values for Adjusting the Roughness of a Channel

ROUGHNESS COEFFICIENTS FOR SHEET FLOW

Table 3 – Roughness Coefficients for Sheet Flow

Surface Description	n[1]
Smooth surfaces (concrete, asphalt, gravel, or	0.011
Fallow (no residue)	0.05
Cultivated soils:	
Residue cover ≤ 20%	0.06
Residue cover ≥ 20%	0.17
Grass:	
Short Grass Prairie	0.15
Dense Grasses	0.24
Bermudagrass	0.41
Range (natural)	0.13
Woods:	
Light Underbrush	0.4
Dense Underbrush	0.8

OVERBANK ROUGHNESS COEFFICIENTS

Table 4 - Values of the Manning's Roughness Coefficient *n*[Modified from Chow, 1959, Table 4-1]

Type of Channel and Description	Minimum	Normal	Maximum
Flood Plains			
a. Pasture, no brush			
1. Short grass	0.250	0.030	0.035
2. High grass	0.300	0.035	0.050
b. Cultivated areas			
1. No crop	0.020	0.030	0.040
2. Mature row crops	0.025	0.035	0.045
3. Mature field crops	0.030	0.040	0.050
c. Brush			
1. Scattered brush, heavy weeds	0.035	0.050	0.070
2. Light brush and trees, in winter	0.035	0.050	0.060
3. Light brush and trees, in winter	0.040	0.060	0.080
4. Medium to dense brush, in winter	0.045	0.070	0.110
5. Medium to dense brush, in summer	0.070	0.100	0.160
d. Trees			
1. Dense willows, summer, straight	0.110	0.150	0.200
2. Cleared land with tree stumps, no sprouts	0.030	0.040	0.050
3. Same as above, but with heavy growth of sprouts	0.050	0.060	0.080
4. Heavy stand of timber, a few down trees, little undergrowth, flood stage below branches	0.080	0.100	0.120
5. Same as above, but with flood stage reaching branches	0.100	0.120	0.160

Sturm, T.W. *Open Channel Hydraulics*. New York: McGraw-Hill, 2001.

VALUES FOR ADJUSTING ROUGHNESS OF A CHANNEL

Table 5 - Adjustment Values for Factors that Affect the Roughness of a Channel [Modified from Aldridge and Garrett, 1973, Table 2]

Channel conditions		*n* value adjustment[a]	Example
Degree of Irregularity (n_1)	Smooth	0.0000	Compares to the smoothest channel attainable in a given bed material
	Minor	0.001-0.005	Compares to carefully dredged channels in good condition but having slightly eroded or scoured side slopes
	Moderate	0.006-0.010	Compares to dredged channels having moderate to considerable bed roughness and moderately sloughed or eroded side slopes
	Severe	0.011-0.020	Badly sloughed or scalloped banks of natural streams; badly eroded or sloughed sides of canals or drainage channels; unshaped, jagged, and irregular surfaces of channels in rock
Variation in channel cross-section (n_2)	Gradual	0.0000	Size and shape of channel cross-sections change gradually
	Alternating occassionally	0.001-0.005	Large and small cross-sections alternate occassionally, or the main flow occassionally shifts from side to side owing to changes in cross-sectional shape
	Alternating frequently	0.010-0.015	Large and small-cross-sections alternate frequently, or the main flow frequently shifts from side to side owing to changes in cross-sectional shape
Effect of obstruction (n_3)	Negligible	0.000-0.004	A few scattered obstructions, which include debris deposits, stumps, exposed roots, logs, piers, or isolated boulders, that occupy less than 5 percent of the cross-sectional area
	Minor	0.005-0.015	Obstructions occupy less than 15 percent of the cross-sectional area, and the spacing between obstructions is such that the spehere of influence around one obstruction does not extend to the sphere of influence around another obstruction. Smaller adjustments are used for curved smooth-surfaced objects than are used for sharp-edged angular objects.
	Appreciable	0.020-0.030	Obstructions occupy from 15 to 50 percent on the cross-sectional area, or the space between obstructions is small enough to cause the effects of several obstructions to be additive, thereby blocking an equivalent part of a cross section
	Severe	0.040-0.050	Obstructions occupy more than 50 percent of the cross-sectional area, or the space between obstructions is small enough to cause turbulence across most of the cross section
Amount of vegetation (n_4)	Small	0.002-0.010	Dense growths of flexible turf grass, such as Bermuda, or weeds growing where the average depth of flow is at least two times the height of the vegetation; supple tree seedlings such as willow, cottonwood, arrowweed, or saltcedar growing where the average depth of flow is at least three times the height of the vegetation
	Medium	0.010-0.025	Turf grass growing where the average depth of flow is from one to two times the height of the vegetation; moderately dense stemmy grass, weeds, or tree seedlings growing where the avearge depth of flow is from two to three times the height of the vegetation; brushy, moderately dense vegetation, similar to 1-to 2-year-old willow trees in the dormant season, growing along the banks, and no significant vegetation is evident along the channel bottoms where the hydraulic radius exceeds 2 feet
	Large	0.025-0.050	Turf grass growing where the average depth of flow is about equal to the height of the vegetation; 8- to 10-year-old willow or cottonwood trees intergrown with some weeds and brush (none of the vegetation in foilage); and no significant vegetation exists along channel botttoms where the hydraulic radius is greater than 2 feet
	Very Large	0.050-0.100	Turf grass growing where the average depth of flow is less than half the height of the vegetation; bushy willow trees about 1 year old intergrown with weeds along side slopes (all vegetation in full foilage), or dense cattails growing along channel bottom; trees intergrown with weeds and brush (all vegetation in full) foilage).

Table 5 - Continued

Channel conditions		*n* value adjustment*	Example
Degree of meandering[2] *(m)*	Minor	1.0000	Ratio of the channel length to valley length is 1.0 to 1.2
	Apprciable	1.1500	Ratio of the channel length to valley length is 1.2 to 1.5
	Severe	1.3000	Rato of the channel length to valley length is greater than 1.5

[1] Adjustments for degree of irregularity, variations in cross section, effect of obstructions, and vegetation are added to the base n value (Table 1) before multiplying by the adjustment for meander.

[2] Adjustment values apply to flow confined in the channel and do not apply where downvalley flow crosses meanders.

Cowan, W.L. *Estimating Hydraulic Roughness Coefficients.* Agricultural Engineering, 37(7), pp. 473-475, 1956.

APPENDIX B – DETERMINING SCS CURVE NUMBERS

NIPS Land-use for Fort Sheridan Ravines

Table 6 – SCS Curve Numbers by Land-Use and Soil Classification Group

NIPC Landuse for Fort Sheridan Ravines		Curve Numbers for Hydrologic Soil Groups				
		A	B	C	D	NRCS Cover Type
	URBAN & BUILT-UP LAND					
1100	RESIDENTIAL	67	78	86	89	
1110	Single Duplex and Townhouse Units	61	75	83	87	Residential: 1/4 acre avg. lot size (100' x 100')
1120	Farmhouse	51	68	79	84	Residential: 1 acre avg. lot size
1130	Multi-Family	77	85	90	92	Residential: 1/8 acre avg. lot size (75' x 75')
1140	Mobile Home Parks and Trailer Courts	77	85	90	92	Residential: 1/8 acre avg. lot size (75' x 75')
1200	COMMERCIAL AND SERVICES	86	90	93	94	
1210	Primary Retail/Service	89	92	94	95	Urban Districts: Commercial & Business
1211	Shopping Malls	89	92	94	95	Urban Districts: Commercial & Business
1212	Retail Centers	89	92	94	95	Urban Districts: Commercial & Business
1220	Primarily Office/Professional	89	92	94	95	Urban Districts: Commercial & Business
1221	Office Campus/Research Park	77	84	89	91	75% Commercial & Business, 25% Open Space
1222	Single-Structure Office Building	77	84	89	91	75% Commercial & Business, 25% Open Space
1223	Business Park	77	84	89	91	Urban Districts: Commercial & Business
1230	Urban Mix	89	92	94	95	Urban Districts: Commercial & Business
1231	Urban Mix With Dedicated Parking	89	92	94	95	Urban Districts: Commercial & Business
1232	Urban Mix , No Dedicated Parking	89	92	94	95	Urban Districts: Commercial & Business
1240	Cultural/Entertainment	89	92	94	95	Urban Districts: Commercial & Business
1250	Hotel/Motel	89	92	94	95	Urban Districts: Commercial & Business
1300	INSTITUTIONAL	71	81	87	90	
1310	Medical and Health Care Facilities	64	77	84	88	50% Commercial & Business, 50% Open Space
1320	Educational	64	77	84	88	50% Commercial & Business, 50% Open Space
1330	Governmental administration and services	89	92	94	95	Urban Districts: Commercial & Business
1340	Prisons and Correctional Facilities	89	92	94	95	Urban Districts: Commercial & Business
1350	Religious Facilities	77	84	89	91	75% Commercial & Business, 25% Open Space
1360	Cemeteries	39	61	74	80	Open Space: Good
1370	Other Institutional	77	84	89	91	75% Commercial & Business, 25% Open Space
1400	INDUSTRIAL AND WAREHOUSING AND WHOLESALE TRADE	81	88	91	93	
1410	Mineral Extraction	81	88	91	93	Urban Districts: Industrial
1420	Manufacturing and Processing	81	88	91	93	Urban Districts: Industrial
1430	Warehousing/Distribution Center	81	88	91	93	Urban Districts: Industrial
1440	Industrial Park	81	88	91	93	Urban Districts: Industrial
1500	TRANSPORTATION, COMMUNICATION, AND UTILITIES	75	84	89	91	
1510	Automotive Transportation	83	89	92	93	Streets & Road: Paved-Open Ditches (Including ROW)
1511	Interstate and Tollway	83	89	92	93	Streets & Road: Paved-Open Ditches (Including ROW)
1512	Other Roadway	83	89	92	93	Streets & Road: Paved-Open Ditches (Including ROW)

Table 6 - Continued

		Curve Numbers for Hydrologic Soil Groups				
		A	B	C	D	NRCS Cover Type
1520	Other Linear Transportation w/ Assoc. Facilities	83	89	92	93	Streets & Road: Paved-Open Ditches (Including ROW)
1530	Aircraft Transportation	83	89	92	93	Streets & Road: Paved-Open Ditches (Including ROW)
1540	Independent Parking	98	98	98	98	Impervious Areas: Paved Parking Lots
1550	Communication	49	69	79	84	Open Space: Fair Condition
1560	Utilities & Waste Facilities	39	61	74	80	Open Space: Good
	AGRICULTURAL LAND					
2100	Row Crops, Grains, & Grazing	64	75	83	86	Open Space: Good
2200	Nurseries, Greenhouses, Orchards, Tree Farms, & Sod Farm	64	75	83	86	Open Space: Good
2300	Agricultural , Other	64	75	83	86	Open Space: Good
	OPEN SPACE					
3100	Open Space, Primarily Recreational	39	61	74	80	Open Space: Good
3200	Golf Courses	39	61	74	80	Open Space: Good
3300	Open Space, Primarily Conservation (Forest & Natural Preserves	39	61	74	80	Open Space: Good
3400	Hunting Clubs, Scout Camps, & Private Campgrounds	39	61	74	80	Open Space: Good
3500	Linear Open-Space Corridors	39	61	74	80	Open Space: Good
3600	Other Open Space	39	61	74	80	Open Space: Good
	VACANT AND WETLANDS					
4100	VACANT LAND	35	62	76	83	Open Space: Good
4110	Forest and Grassland	30	55	70	77	Woods: Good
4120	Wetlands	40	68	81	88	Meadow (+10)
4200	UNDER DEVELOPMENT OR CONSTRUCTION	50	68	79	84	Open Space: Fair Condition
4210	Residential	61	75	83	87	Residential: 1/4 acre avg. lot size (100' x 100')
4220	Non-Residential Includes Unidentifiable Lots	39	61	74	80	Open Space: Good
4300	OTHER VACANT	39	61	74	80	Open Space: Fair Condition
	WATER					
5100	Rivers, Streams & Canals	98	98	98	98	Water (98)
5200	Lakes, Reservoirs & Lagoons	78	89	96	98	Pasture, Grassland: Poor (+10)
5300	Lake Michigan	98	98	98	98	

APPENDIX C – REFERENCES FOR DETERMINING SYNTHETIC PRECIPITATION

LCSMC Watershed Development Ordinance, Rainfall Depth-Duration Frequency
LCSMC Watershed Development Ordinance, Huff Quartile Distributions

Table 7 – LCSMC Watershed Development Ordinance, Rainfall Depth-Duration Frequency (*Watershed Development Ordinance*. Lake County Stormwater Management Commission. 2008.)

Rainfall Depth-Duration Frequency Tables for Lake County
Rainfall is in inches

Duration	1 year	2 year	5 year	10 year	25 year	50 year	100 year	*Mult. factor
5 min	0.28	0.34	0.41	0.47	0.57	0.66	0.78	0.12
10 min	0.49	0.59	0.71	0.81	1.00	1.16	1.37	0.21
15 min	0.63	0.76	0.92	1.05	1.28	1.49	1.76	0.27
30 min	0.87	1.04	1.26	1.44	1.76	2.04	2.41	0.37
1 hour	1.10	1.32	1.60	1.82	2.23	2.59	3.06	0.47
2 hour	1.36	1.62	1.97	2.25	2.76	3.19	3.77	0.58
3 hour	1.50	1.79	2.18	2.48	3.04	3.52	4.16	0.64
6 hour	1.76	2.10	2.55	2.91	3.56	4.13	4.88	0.75
12 hour	2.04	2.44	2.96	3.38	4.13	4.79	5.66	0.87
18 hour	2.21	2.63	3.20	3.65	4.47	5.17	6.11	0.94
24 hour	2.35	2.80	3.40	3.88	4.75	5.50	6.50	1.00
48 hour	2.54	3.02	3.67	4.19	5.13	5.94	7.02	1.08
72 hour	2.73	3.25	3.94	4.50	5.51	6.38	7.54	1.16
120 hour	***3.08***	***3.67***	***4.45***	***5.08***	***6.22***	***7.21***	***8.52***	***1.31***
240 hour	***3.45***	***4.12***	***5.00***	***5.70***	***6.98***	***8.09***	***9.56***	***1.47***

References: Bulletin 70, Illinois State Water Survey Champaign, 1989

*Multiplication Factor - Average ratios of X-hour/24-hour rainfall for Illinois, 1989 Bulletin 70.

Table 8 - LCSMC Watershed Development Ordinance, Huff Quartile Distributions (*Watershed Development Ordinance*. Lake County Stormwater Management Commission. 2008.)

HUFF QUARTILE DISTRIBUTIONS												
CUMUL.	AREA < 10 SM				AREA > 10 & AREA < 50				AREA > 50 & AREA < 400			
STORM	HUFF QUARTILE				HUFF QUARTILE				HUFF QUARTILE			
PERCENT	1st	2nd	3rd	4th	1st	2nd	3rd	4th	1st	2nd	3rd	4th
05	16	03	03	02	12	03	02	02	08	02	02	02
10	33	08	06	05	25	06	05	04	17	04	04	03
15	43	12	09	08	38	10	08	07	34	08	07	05
20	52	16	12	10	51	14	12	09	50	12	10	07
25	60	22	15	13	62	21	14	11	63	21	12	09
30	66	29	19	16	69	30	17	13	71	31	14	10
35	71	39	23	19	74	40	20	15	76	42	16	12
40	75	51	27	22	78	52	23	18	80	53	19	14
45	79	62	32	25	81	63	27	21	83	64	22	16
50	82	70	38	28	84	72	33	24	86	73	29	19
55	84	76	45	32	86	78	42	27	88	80	39	21
60	86	81	57	35	88	83	55	30	90	86	54	25
65	88	85	70	39	90	87	69	34	92	89	68	29
70	90	88	79	45	92	90	79	40	93	92	79	35
75	92	91	85	51	94	92	86	47	95	94	87	43
80	94	93	89	59	95	94	91	57	96	96	92	54
85	96	95	92	72	96	96	94	74	97	97	95	75
90	97	97	95	84	97	97	96	88	98	98	97	92
95	98	98	97	92	98	98	98	95	99	99	99	97

References: *Floyd A. Huff and James R. Angel, 1989 "Frequency Distributions and Hydroclimatic Characteristics of Heavy Rainstorms in Illinois', Illinois State Water Survey, Bulletin 70.*

APPENDIX D – RECOMMENDED PLAN DESIGN CALCULATION SHEETS

US Army Corps of Engineers Chicago District	PROJECT TITLE: Ravine 8	COMPUTED BY: JAF	DATE:	SHEET: 1 of 3	
	STRUCTURE TITLE:	CHECKED BY:	DATE:	CONTRACT NO:	

Measure HA - Open Channel Conveyance

Assumptions
- Flow from head not attenuated; must mitigate downstream
- Vegetated fully developed

Inlet Design at Head

* Provide plunge pool at head

From HEC-14, scour hole dimension, Eqn. 5.2

$$A = \frac{\pi D^2}{4} = \frac{\pi (2.5ft)^2}{4} = 4.909 ft^2 \Rightarrow Y_e = \left(\frac{A}{2}\right)^{1/2} = \left(\frac{4.909 ft^2}{2}\right)^{1/2} = 1.57 ft$$

$L = 15ft \quad W = 9ft.$

Estimate D_{50},

$$\frac{h_s}{Y_e} = 0.86\left(\frac{D_{50}}{Y_e}\right)^{-0.55}\left(\frac{V_o}{\sqrt{gY_e}}\right) - C_o$$

where $h_s = 1ft \quad Y_e = 1.57ft$

$V_o = 1.6 V_{model} = 1.6(9.01 ft/s) = 14.4 ft/s$

$C_o \sim 2$

use $D_{50} = 0.5ft$, $h_s = 1ft$ check $\frac{D_{50}}{Y_e} = 0.318 > 1$ ok!

$\frac{h_s}{D_{50}} = 2 \geq 2$ ok!

From HEC-RAS results, position riffles at:
- Estimate stable slope from HEC-RAS results

XS 436 → use 345 to 426

$$S_f = \frac{3.40}{90.39} = 0.04$$

XS 727 to XS 512

$S_o = 0.0703$

$H = (0.0703 - 0.04)(727.2 - 512.7) = 7.0ft$

$\frac{H}{h} = \frac{7ft}{0.5f} = 14 \Rightarrow$ use (14) riffles

$$\text{Spacing} = \frac{(727.2ft - 512.7ft)}{14} = 15.3ft.$$

US Army Corps of Engineers Chicago District	PROJECT TITLE: Ravine 8	COMPUTED BY: JAF	DATE:	SHEET: 2 of 3	
	STRUCTURE TITLE:	CHECKED BY:	DATE:	CONTRACT NO:	

* Since cells are pre-filled, assume design velocity over structures

$V_{des} = 1.6 V_{mod} = 1.6(3.5 ft/s) = 5.6 ft/s$

$C = 0.45 \quad d \sim 0.6 ft.$

$$D_{30} = 0.45(0.3 ft)\left[(0.78)\left(\frac{5.6 ft/s}{\sqrt{32.2 ft/s^2 \cdot 0.3}}\right)\right]^{2.5} = 0.3 ft.$$

<u>XS 224 to 200ft above mouth</u>

$S_o = 0.06$

$H = (0.06 - 0.04)(24 ft) = 0.48 ft.$

$\frac{H}{h} = \frac{0.48 ft}{0.5 ft} = 0.96 \rightarrow$ use (1) riffle

$C = 0.45 \quad d = 0.3 ft \Rightarrow D_{30} = 0.3 ft.$

<u>Final Slope to Mouth</u>

* Assume final elevation of 608

$S_o = \frac{608 - 583}{200 ft} = 0.125$

$H = (0.125 - 0.04)(200 ft) = 17 ft$

$\frac{H}{h} = \frac{17 ft}{1.5 ft} = 11.3 \rightarrow$ use (12) riffles

$\text{Spacing} = \frac{200 ft}{12} = 16.7 ft$

$V_{des} = 1.6 V_{mod} = 1.6(3.5 ft/s) = 5.6 ft/s$

$C = 0.45 \quad d = 0.3 \quad D_{30} = 0.3 ft.$

US Army Corps of Engineers Chicago District	PROJECT TITLE: Ravine 8	COMPUTED BY: JAF	DATE:	SHEET: 3 of 3
	STRUCTURE TITLE:	CHECKED BY:	DATE:	CONTRACT NO:

Measure HB - In-Ravine Pipe Conveyance

Assumptions:

- Final grading approximately the same as existing condition
- Only sign of potential instability in ravine tributaries are small, narrow gullies (consistent w/ low flow-high velocity discharges on bare soil)
- Estimate stable slope for preliminary design using HEC-RAS results:

  XS345 → use 345 to 426

  $S_f = \frac{3.40}{90.89} = 0.04$

- Single 30" pipe buried below approx. 24" of cover

From HEC-RAS results, position riffles at:

Final Slope to Mouth

$S_o = \frac{608 - 583}{200} = 0.125$

$H = (S_o - S_f)L = (0.125 - 0.04)(200) = 17\,ft$

$\frac{H}{h} = \frac{17\,ft}{1.5\,ft} = 11.3 \Rightarrow$ use (12) riffles

Spacing $= \frac{200\,ft}{12} = 16.7\,ft$

$V_{des} = 1.6 V_{mod} = 1.6(3.5\,ft/s) = 5.6\,ft/s$

$C = 0.45 \quad d = 0.3\,ft \quad D_{30} = 0.3\,ft$

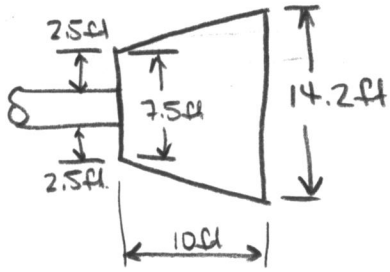
Stone Apron at Mouth

$Q_{des} = 2Q_{mod} = 2(25.2\,cfs) = 50.4\,cfs$

From HEC-14, eqn. 10-5

$$D_{50} = 0.2D\left(\frac{Q}{\sqrt{g}D^{2.5}}\right)^{4/3}\left(\frac{D}{TW}\right)$$

$$= 0.2(2.5\,ft)\left[\frac{50.4\,cfs}{\sqrt{32.2\,ft/s^2}\,(2.5\,ft)^{2.5}}\right]^{4/3}\left(\frac{2.5\,ft}{0.4 \cdot 2.5\,ft}\right) = 1.1\,ft$$

$L = 4D = 4(2.5\,ft) = 10\,ft$

Depth $= 3.3D_{50} = 3.3(1.1\,ft)$
$= 3.6\,ft$